

ACTIVE CONTROL TURBOCHARGER FOR AUTOMOTIVE APPLICATION: AN EXPERIMENTAL EVALUATION

Apostolos Pesiridis and Ricardo Martinez-Botas

Department of Mechanical Engineering

Imperial College London

SW7 2AZ Exhibition Road, London

ABSTRACT

The current paper presents the results from a comprehensive set of experimental tests on a prototype active control turbocharger. This is a continuing series of test work as part of the development of this new type of turbocharger. Driven by the need to comply to increasingly strict emissions regulations as well as a continuing strive for better overall performance the active control turbocharger is intended to provide an improvement over the current state-of-the-art in turbocharging. In this system, the nozzle is able to alter the throat inlet area of the turbine according to the pressure variation of each engine exhaust gas pulse thus imposing a substantially more 'active' form of control of the conditions at the turbine rotor inlet.

NOMENCLATURE

U	blade tip speed	Greek symbols	
\dot{m}	mass flow rate	γ	ratio of specific heats
FGT	Fixed Geometry Turbocharger	η	efficiency
VGT	Variable Geometry Turbocharger	$\theta, \Delta \theta$	Nozzle position and amplitude, respectively
ACT	Active Control Turbocharger	Subscripts	
ER	turbine expansion ratio or pressure ratio	is	isentropic
P	Pressure	act	actual
T	temperature	min	minimum area
Cp	specific heat at constant pressure	max	maximum area
MFP	mass flow parameter, $MFP = \frac{\dot{m}\sqrt{T_0}}{P_0}$	0	total/stagnation condition
		2	pulse generator
U/C_{is}	velocity ratio	3	turbine inlet
MFT	Mixed Flow Turbine	4	turbine exit
LVDT	Linear Variable Displacement Transducer	t	turbine
CFRP	Carbon Fibre Reinforced Plastic	t-s	total to static
FWG	Function Waveform Generator	null	null position of actuator or nozzle

INTRODUCTION

The continuous increase in requirements from charging systems as a part of modern internal combustion engines is driven by the rapid and very demanding introduction of

new emissions legislation, as well as ever higher power density requirements, whilst maintaining or improving the fuel efficiency.

A relatively recently matured and increasingly popular charging technology is the Variable Geometry Turbocharger (VGT). The benefits accrued by the use of variable geometry devices for exhaust gas flow control to the turbine are well known and include improved transient response, fuel economy and more importantly reduced emissions in the face of ever stringent emissions regulations. The common problems encountered with VGT were reliability (for long periods of time while exposed to high temperature and corrosive exhaust gases), complexity because of the VGT actuation mechanism and control system, and subsequent, high cost [1]. However, recent research has tended to provide acceptable solutions to most of these problems and today VGTs have already had a significant impact in the design of small diesel engines.

A fundamental issue that has so far not been addressed satisfactorily, however, is the less than ideal combination of a reciprocating engine providing energy to drive a rotodynamic machine such as a turbocharger turbine. Yet even with the advent of VGTs this mismatch is not eliminated, since a VGT responds to operating point changes only, i.e., for steady-state operation the nozzle setting of a VGT assumes one non-changing, optimal condition. However, regardless of the engine operating at steady-state or transient mode, the inlet conditions to the turbocharger still include a highly pulsating flow field with widely varying pressure and mass flow rate levels at all times [2]. It may still be possible to harness that energy by continually altering the effective throat area of the turbine by means of a fast-response nozzle.

The Active Control Turbocharger (ACT) is a special type of VGT, where the nozzle (in this case a sliding wall-type restrictor) is able to alter the inlet area at the throat of the turbine inlet casing (volute) in phase and at the same frequency as that of the incoming exhaust pulses (Figure 1). For this purpose it is actuated by a suitable electro-dynamic shaker - which supplied by a powerful amplifier – is capable of meeting the frequency and displacement requirements of this intensive and continuous operation.

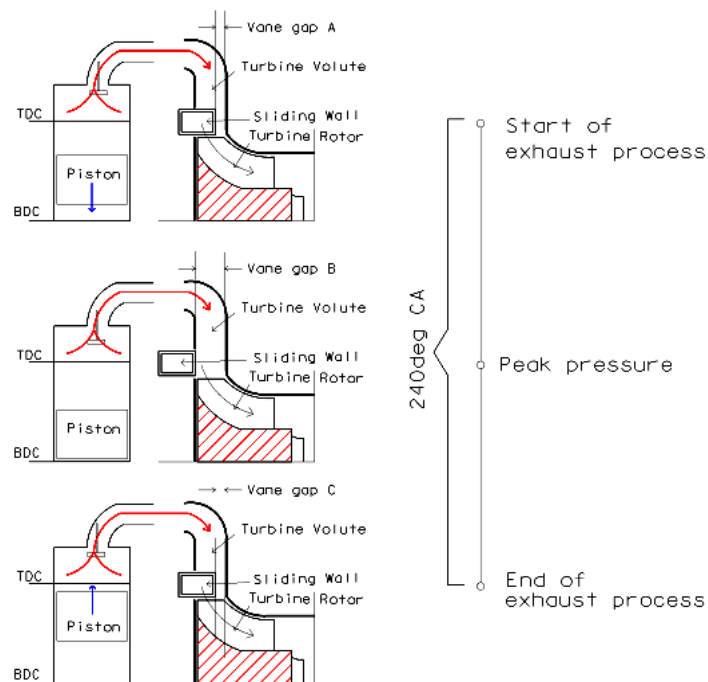


Fig 1 The ACT concept of operation during one Exhaust process cycle (240° CA) depicting adjustment of area as pressure changes during the course of one pulse.

In early production VGTs, open-loop control systems were used to provide the required boost pressure without taking into account engine volumetric efficiency. Current production VGT systems provide closed-loop control with engine volumetric efficiency being taken into account. An undue reduction in volumetric efficiency causes specific fuel consumption and emissions penalties. Excessive volumetric efficiency reduction is the result of excessive negative pressure drop across the engine i.e., when the exhaust manifold pressure instantaneously exceeds the inlet manifold pressure. In variable geometry mechanisms this is the result of excessive inlet area restriction. However, there are a number of mechanisms available to prevent this from happening. Minimum turbine inlet areas need to be imposed in order to avoid this excessive pressure build-up and in the case of ACT operation the minimum inlet area per cycle can be phased in such a way as to avoid the valve overlap period of the engine. Minimal valve overlap is, therefore, a desirable engine characteristic. The minimal inlet areas that were tested were phases of 30°, 60°, 90° and 240° after the exhaust gas pulse start. Since, the valve overlap period occurs at any point after 180° of crankshaft rotation from the time of the exhaust valve opening the 240° and 30° cases are susceptible to poorer results. However, the actual phasing will be a function of exhaust manifold length as well as geometry and the wave dynamics of the particular exhaust process under consideration. The results of these tests are presented in later sections providing a measure of the capability of the ACT concept. In addition, the experimental setup of the laboratory is described and the design and operating details pertaining to ACT are explained.

EXPERIMENTAL TEST FACILITY

The turbocharger aerodynamic test facility is a simulated reciprocating engine test bed for turbocharger testing. In Figure 2(a) a schematic of the laboratory set-up for ACT testing is illustrated. Three screw compressors supply air at room temperature up to a maximum mass flow rate of 1.2 kg/s. A 76kW heater stack is used to bring the air to the required test condition. The pulsations are generated by a pair of counter rotating plates situated 755 mm upstream of the measurement inlet plane. The unsteady flow generated replicates an engine exhaust manifold, albeit operating in cold flow; the non-dimensional mass flow rate and speed parameters are correctly matched. The air flow is split into two pipes soon after leaving the heaters, this feature allows testing of twin entry turbos. The current turbine is part of a single entry system, thus the air flow is merged prior to entering the volute.

Instrumentation

Figure 2(b) shows the hardware setup for high-speed data-logging and ACT control. Various sensors along the pipework upstream of the turbine and on the turbine itself are utilised. Pressures from the measurement plane, and turbine inlet casing stations, CTA (constant temperature hot wire anemometer), LVDT nozzle position and FWG (Function waveform generator) signals are directed to the high-speed analogue input data acquisition and control card, while the signal from the magnetic pickup sensor measuring pulse generator frequency and the signal from the turbine speed optical sensor are directed towards the high-speed, counter timer card.

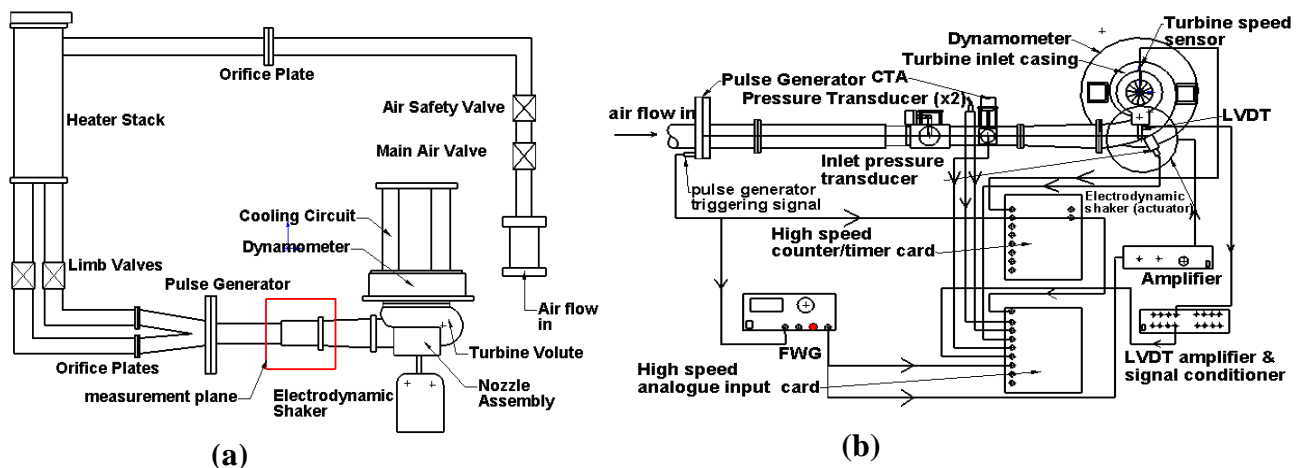


Fig 2 (a) Turbocharger test rig schematic and (b) laboratory schematic of major high-speed data acquisition hardware as well as the set-up for ACT control.

Active control turbocharger

Design

The main ACT components can be seen in Figure 3. A nozzleless Holset H3B turbocharger turbine was modified to accept a nozzle for VGT testing. Due to the very small space available and dynamic requirements, a very thin (1.5mm thickness) section, tubular in shape, sliding nozzle was designed (Figure 4). Two embedded attachment points at the end away from the turbine inlet casing are used to mount the nozzle on to its actuating arm (yoke) via two small bearing pads, which fit between the nozzle and the yoke and assist in translating the pivoting movement of the yoke into a linear motion by the nozzle. The nozzle itself is guided towards the throat by an inner guide, which serves both as a bearing surface to the nozzle as well as forming the exducer section of the turbine. An outer guide houses the entire assembly and at its lower end is shaped into a bracket on which the yoke is attached and can freely pivot about. The entire assembly is held together and attached to the face of the turbine by six 50mm M5 bolts. The throat width to the turbine is 26mm wide and the nozzle can block 21.5mm off that passage width before reaching the stops.

The materials used for the assembly were 6082-T6 aluminium alloy, for the entire assembly except for the nozzle, providing light weight, with adequate strength to overcome (in the case of the yoke) fatigue, which is the major issue in this type of operation. At the most severe operation the yoke achieved a safety factor of 10 with respect to the maximum bending stress applied to it at its corners by the bearing pads. The nozzle was of carbon fibre reinforced plastic (CFRP) construction, providing adequate strength for ultra low weight against the high pressure air flow used during testing - low nozzle weight being critical for the ACT in achieving good force performance.

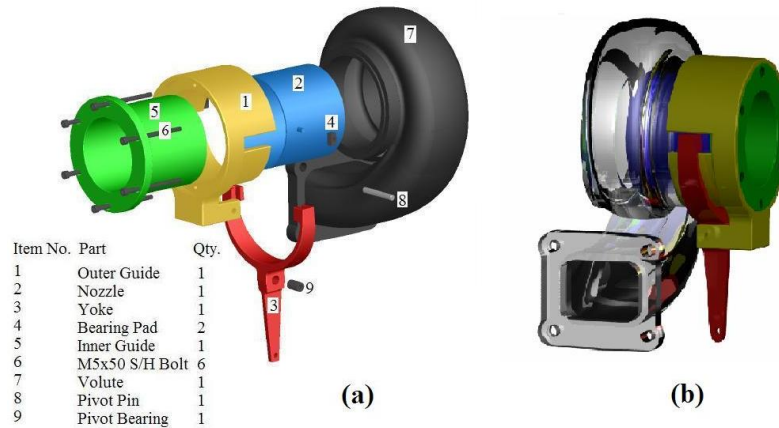


Fig 3 (a) Active control turbocharger exploded view and (b) assembly.

An electrodynamic shaker was used to drive the nozzle in ACT mode (Figure 5). The shaker was chosen so as to be able to provide the required force for the limiting frequencies and amplitudes expected during testing (60Hz and up to 21.5mm, respectively). Direct coupling of the shaker and nozzle was not possible due to the nozzle being driven from the exhaust side of turbine, thus forcing the shaker to be offset to the side of the exducer. The simplest way to drive the nozzle from this position was with a single-piece, pivoting yoke-type actuator arm. This makes the design, simpler, more compact and more importantly allows for far better fatigue endurance with the added advantage of significant vibration damping due to the rocker-arm type operation of the yoke used to drive the nozzle, which largely damps out what would otherwise have been severe vibrations through the turbocharger. The total mass of all moving parts (Part Nos. 2, 3, 4, 8 and 9 in Figure 3(a)) is only 0.241kg, which was important in order to be able to achieve the force performance required for testing, even though it means a penalty in terms of vibration, since at present it is not possible to balance both sides of the yoke, as the top part (nozzle) is significantly lighter to the bottom part that also contains approximately 0.2kg of the moving part of the shaker.

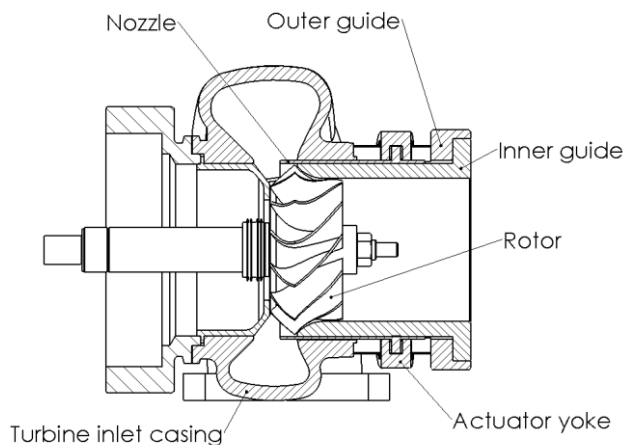


Fig 4 ACT sectional view with MFT rotor 'D'. The thin section nozzle can be seen protruding axially at the inlet to the turbine.

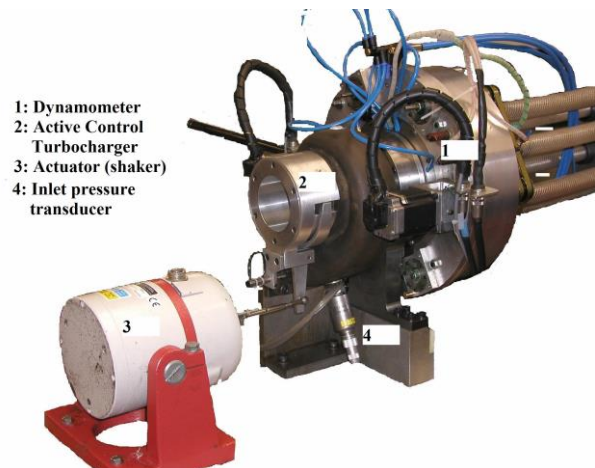


Fig 5 Active control turbocharger with electrodynamic shaker and dynamometer

Operation

The electrodynamic shaker is connected to the lower part of the yoke through an adjustable lever (Figure 2) used to set the nozzle restriction (\mathcal{G}_{VGT}) in VGT mode or the null point (\mathcal{G}_{null}) in ACT mode. For VGT testing once \mathcal{G}_{VGT} is set, its value does not change through either steady or unsteady testing, while for ACT testing \mathcal{G}_{null} is set at the midpoint of the nozzle oscillation amplitude, between the maximum intended open nozzle area point ($\theta_{VGT} = \theta_{max}$) and the minimum area available (see Table 1 below). The amplitude, frequency and form of the controlling signal is controlled by a function waveform generator, which commands a control input in the form of a selected waveform to a 100W amplifier as well as to the controlling computer. From the amplifier the signal is routed to the shaker and transformed into motion of the nozzle. High speed pressure transducers located at the measurement plane as well as just upstream of the nozzle are used to measure the inlet pressure level. Timing is achieved through the use of the magnetic pickup sensor on the pulse generator to define accurately the pulse period and its start and end. The pulse generator opening signal is used to trigger the FWG, which in turn causes the nozzle to move in response to its signal. The known length of the pipework from the pulse generator to the nozzle is used to derive the pressure wave travel time, which travels at the acoustic velocity [3]. In addition the total system (control input to feedback) time response is known through testing and a time constant is thus derived that is input into the controlling software that controls operation of the ACT. Thus, the shaker is always in phase with the inlet pressure signal. Additional out-of-phase, resulting due to the fact that the total energy travel time is dependent on both the acoustic velocity of the pressure wave in addition to the local flow velocity [3], is detected through suitable software and adjusted manually as required, thus achieving a reasonably accurate phasing of inlet pressure and nozzle signals. All acquired data are phase shifted (lagged) eventually, from their measurement location (Figure 2(b)) to the turbine inlet entry according to the procedure described in [3].

For VGT testing \mathcal{G}_{VGT} can be set by adjusting the lever only. For ACT testing, \mathcal{G}_{null} is adjusted manually, while $\Delta\mathcal{G}_{ACT}$ and the shaker frequency are preset on the waveform generator according to the test parameters required. Typical \mathcal{G}_{VGT} test points used during testing are included in Table 1 below (in normalized throat open area form):

Table 1 Nozzle VGT settings for the 26mm wide throat area

Nozzle restriction into throat (mm)	\mathcal{G}_{VGT} (%)
0	100 (Fully open area)
4	84.6
8	69.2
12	53.8
16	38.5
20	23.1
21.5	17.3 (Fully restricted area)

EXPERIMENTAL RESULTS

The parameters tested included effects of varying frequency of exhaust pulses (engine rpm), different turbine rotational speeds and loads (expressed in millimetres distance

between the rotating eddy current dynamometer magnet and the two equi-spaced stators on either side with 10mm being the lowest and 0.5mm the highest load, respectively) set against a specific amount of isentropic energy provided upstream of the turbine. In addition, varying nozzle oscillating amplitudes ($\Delta\theta$) in ACT operation as well as the effect of different nozzle input signal phasings in relation to a baseline VGT inlet pressure trace were tested.

The unsteady tests were carried out at three different VGT settings, 38.5%, 53.8% and 69.2% open throat area. These formed the reference point against which all the ACT tests are compared. Unlike the original idea to extract energy only at the lower (near ambient) energy levels of the pulse (Figure 1) where the minimum area provided by the nozzle occurs when the maximum throat area and the peak of the pulse are in-phase (i.e., the minimum area occurs 240° after pulse generator opening. Three other minimum nozzle area phase settings were tested: one, 30° after pulse generator opening, the second at 60° (at the nominal peak of the pulse) and the third at 90°. Figure 6, illustrates a reference inlet pressure signal of the VGT operating at a nominal constant 53.8% open throat area. The ACT nozzle amplitude during testing reached a maximum area equal to the VGT setting illustrated and a minimum area equal to the minimum physically possible (17.3%). The effect of the different phase settings is illustrated. The reason for reducing to a minimum the available throat area, at these four different points in the pulse was in order to evaluate the effect that these would have on energy extraction, which is the aim of this project. Indeed as already illustrated in previous work on this rig [3] the amount of energy available for a proportion of the pulse period is indeed negligible and, therefore, a modest overall energy extraction is to be expected from this region.

Figure 7, illustrates the point of using phase settings other than 240°. This particular phase is barely an improvement over the basic VGT setting, but the 30° and 90° settings are notable improvements, while the 60° represents a very substantial improvement over the reference VGT trace.

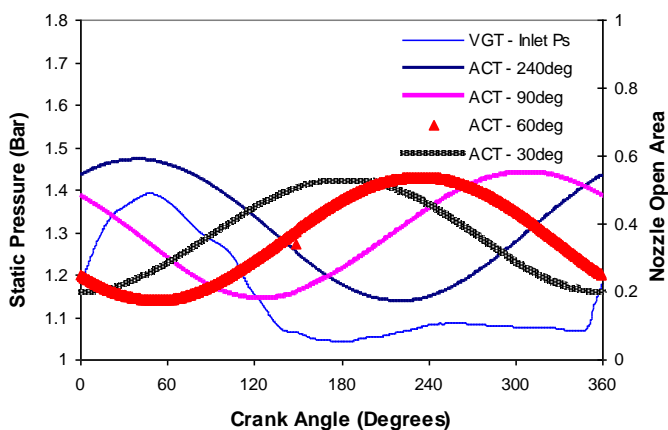


Fig 6 Four different phasing schemes of the ACT nozzle oscillation tested, shown here along with the baseline VGT inlet pressure signal.

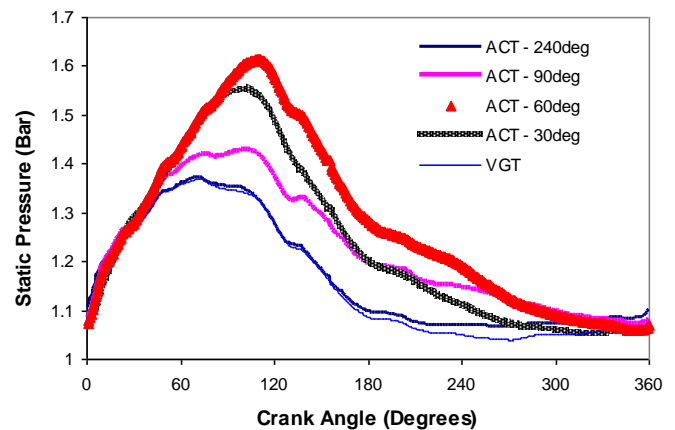


Fig 7 Four ACT inlet pressures at different phases, shown here along with the baseline VGT inlet pressure signal.

Figure 8, shows the equivalent energy extraction in terms of actual power for two different frequencies (40Hz and 60Hz) and at different loads. It is noteworthy that at the pulse peak the 90° setting achieves lower energy extraction than either the 240° setting or the VGT and FGT. This is due to the comparatively lower efficiency attained due to a

certain area restriction already present at the peak due to the sinusoidally actuated nozzle. When the area restriction increases it becomes more optimum and the efficiency improves by comparison to the baseline and there clear work extraction is achieved. This phenomenon can be, also, observed in Figure 9.

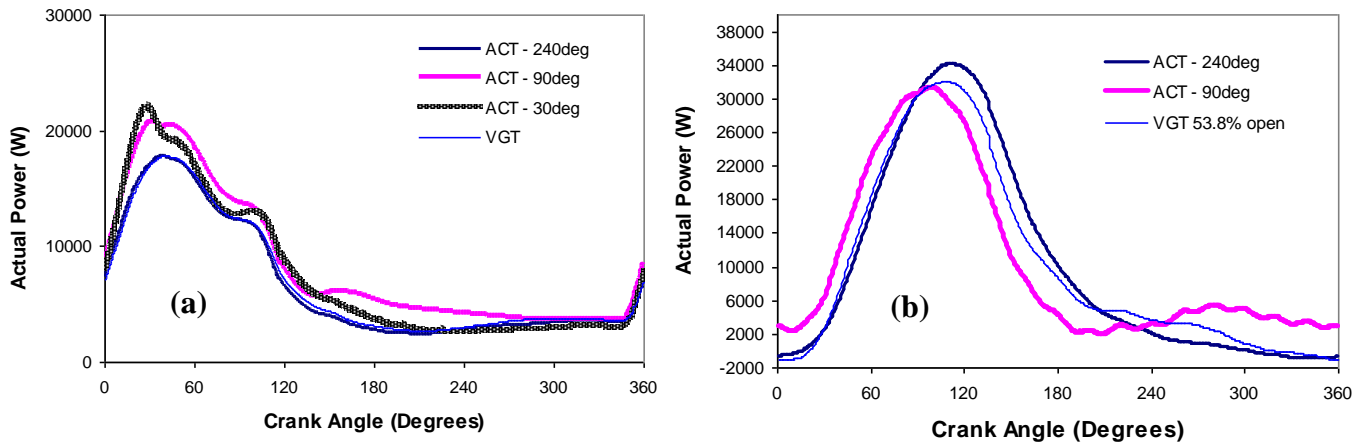


Fig 8 (a) ACT actual power absorbed against the baseline VGT actual power recovered at 60Hz, 4mm load and (b) at 40Hz and 3mm load.

With reference to Figure 6, while at the pressure peak the other settings have a maximum throat area, the 90° setting due to its phasing has less than 40% available throat area. The consequence of this is higher pressure drop but a reduction in efficiency which may locally reduce the amount of power recovered. This is a well recorded trade-off of variable inlet area turbines [4, 5, 6, 7 and 8]. However, in cycle-average terms there is a clear benefit from this type of operation as indicated by Table 2 below for the case of 60Hz at 4mm load:

Table 2 ACT energy extraction benefit over VGT at 60Hz, 4mm load.

	VGT	ACT1 - 240deg	ACT2 - 90deg	240 deg - %Increase	90deg - % Increase
Wact (W)	5495	5667	5902	3.13	7.41
ER	1.55	1.74	1.69	12.57	9.18

A 7.4% increase in actual power is observed for the 90° setting and a 3.13% for the 240° setting when compared to the reference VGT setting. This proves the superiority of the former setting although a useful increase is achieved by the 240° case as well. In the 40Hz case in Table 3 below, all four different settings are presented. The most beneficial phase setting among the four tested was, predictably, the 60° setting. This is due to the fact that the minimum throat area is in-phase with the peak energy levels of the pulse. However, this means a larger trade-off with efficiency and therefore the end improvement is not significantly higher than the 90° case.

Table 3 ACT energy extraction benefit over VGT at 40Hz, 5mm load.

	VGT	ACT - 30deg	ACT - 60deg	ACT - 90deg	ACT - 240deg	30deg-% Increase	60deg-% Increase	90deg-% Increase	240deg-% Increase
Wact (W)	1904	2001	2043	2040	1963	5.12	7.31	7.18	3.09
ER	1.29	1.39	1.44	1.38	1.31	6.97	10.94	6.71	1.42

In Figure 9, the equivalent efficiency fluctuations over the pulse cycle are given. The low efficiency levels at the ends of each pulse are evident. This is where the energy levels of the pulse drop to near ambient conditions and where the efficiency suffers most. As mentioned previously, the improvement in efficiency at the beginning and end of the pulse is evident with a loss approximately 90° after the start of the pulse due to the less than optimum small area restriction present when compared to the baseline VGT area restriction.

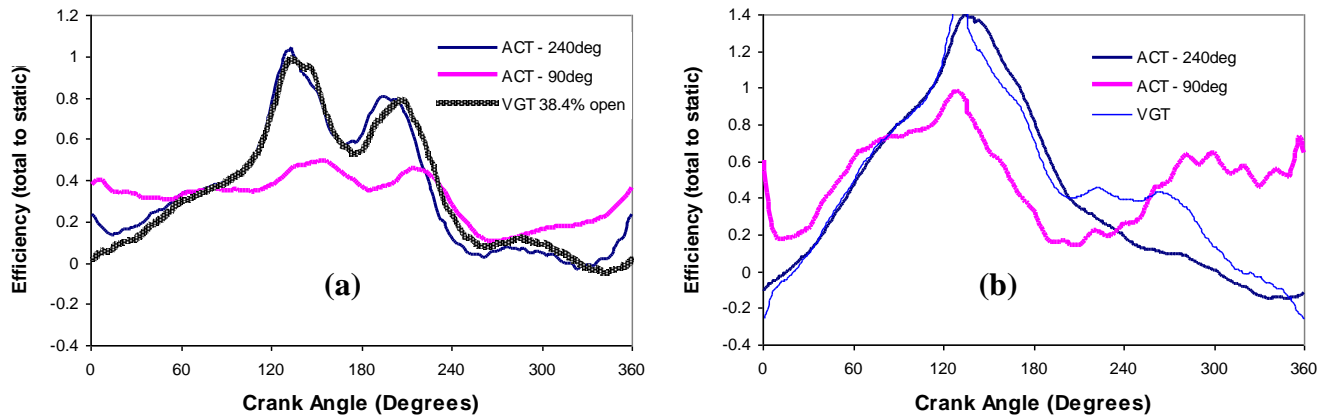


Fig 9 (a) ACT efficiency variation at 60Hz, 4mm load and (b) at 40Hz and 3mm load.

Another way of presenting the effect of active control at the turbine inlet is given in the form of unsteady turbine maps in Figure 10. In this case at 40Hz the behaviour of the turbine is effectively quasi-steady. Energy recovery is evident by shifting of the loops towards the right on the x-axis i.e., towards a higher expansion ratio starting at its lowest from the reference VGT loop and at its highest with the 60° setting.

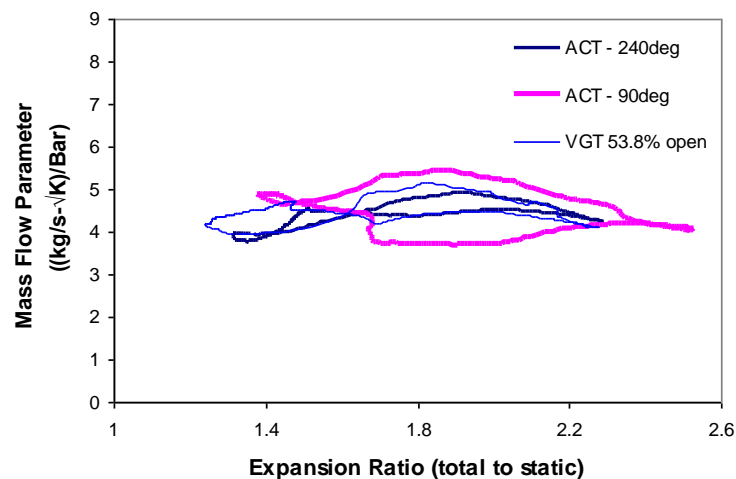


Fig 10 ACT mass flow parameter variation with expansion ratio at 40Hz, 3mm load.

CONCLUSIONS

In addition to the development background on the design of the Active Control Turbocharger prototype and the experimental setup, a wide range of unsteady testing on an ACT was presented.

A notable potential was demonstrated at different loads and turbine speeds. In this case 50% and 70% speed results are presented with powers ranging from 1kW to 10kW cycle averaged with an amplitude of over 30kW. Actual power recovered ranges on average between 3% and 7% depending on nozzle area phasing throughout the range of testing carried out while pressure recovery is even higher but with an efficiency drop as a trade-off at certain periods when the area restriction is not significant.

The potential of this system, however, noteworthy, is still hampered by the less than ideal match of the sleeve nozzle to a MFT inlet due to the creation of a relatively large interspace area formed between the nozzle and the turbine, which is responsible for part of the loss experienced by this turbine, as the flow is allowed to expand again for some distance before reaching the turbine rotor. A more specific design to match a nozzle mechanism to a MFT is already underway offering substantially greater improvement.

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